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A New Variable Reluctance Motor Utilizing Auxiliary Commutation Winding

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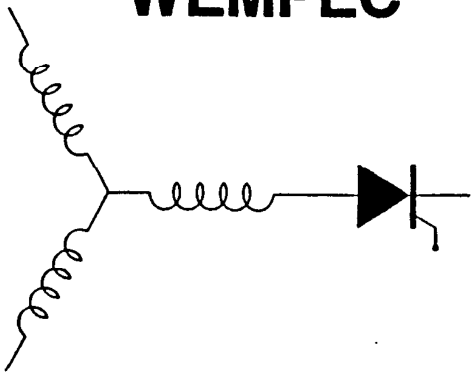

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Abstract-A new concept for solving the current commutation and energy circulation problems in conventional variable reluctance motors (VRMs) is presented. The concept enables the energy stored in the magnetic field to be retained and utilized within the motor instead of being returned to the source. A new VRM and two companion converters are proposed and described in this paper. The operating principles of the motor and the converters are presented. Simulation results based on a linear model are presented to demonstrate the degree of improvement that can be realized. By eliminating these two problems, this new motor has important performance advantages over conventional VRMs.

1. INTRODUCTION

It is well known that the short pitch concentrated windings and doubly salient structure of conventional variable reluctance motors (VRMs) provide this motor with performance advantages such as simple and robust motor and converter structures, high efficiency, good reliability, high speed capability, good thermal characteristics and low cost. However, these features also give rise to undesired characteristics such as relatively high torque ripple, high nonlinearity, current commutation difficulties and excessive energy circulation [1-5]. The difficulty in solving these problems have resulted in slow acceptance of such machines in most applications. In this paper a solution for the two of the most perplexing problems concerning VRMs, namely current commutation and energy circulation is proposed [6].

1.1 Current Commutation

It is important that the phase currents of a VRM be increased to its desired value or to decreased to zero as quickly as possible in order to achieve best utilization of the torque-producing capacity of the motor. Unfortunately, the presence of the motor phase inductance prevents the current from changing instantaneously. The situation becomes worst when the rotor is in the aligned position because the inductance reaches its maximum value while the phase has to be turned off (motoring) or turned on (generating) at that moment. Because of this high inductance, each phase of a VRM in motoring mode has to be turned off considerably before the alignment position is achieved. This leads to poor utilization of the torque-producing capability of the motor. It has been reported that for a 10 HP VRM, if there were no voltage limitation on the semiconductor devices then the currents would approach the ideal waveform and the output would be 65% higher than its rated output [7]. For the same reason, the output power of a VRM in the generating mode is much less than that of the ideal case because the phase current can not increase as rapidly as desired. Obviously, power output of motor structures can be substantially increased or, conversely, motor size can be considerably reduced for a given power rating if this problem can be overcome.

1.2 Energy Circulation

It is well known that not all of the input energy can be converted to mechanical form in a conventional VRM. As shown in Fig. 1, the energy converted to mechanical form, represented by the area W_1, is only a part of the total input energy, which is represented by the areas W_1 and W_2. The energy represented by the area W_2 is returned back to the source after each "stroke" or current pulse. For a VRM operated as a generator, there also the same portion of energy flowing back and forth between the source and motor. This problem is also called the "excitation penalty" [8] and it becomes more severe as the motor size decreases. Since the energy circulation between the motor and converter causes extra motor losses and creates a need for a larger DC bus capacitor and converter switch rating, solving this problem can result in a motor having a higher system efficiency as well as a lower cost converter.

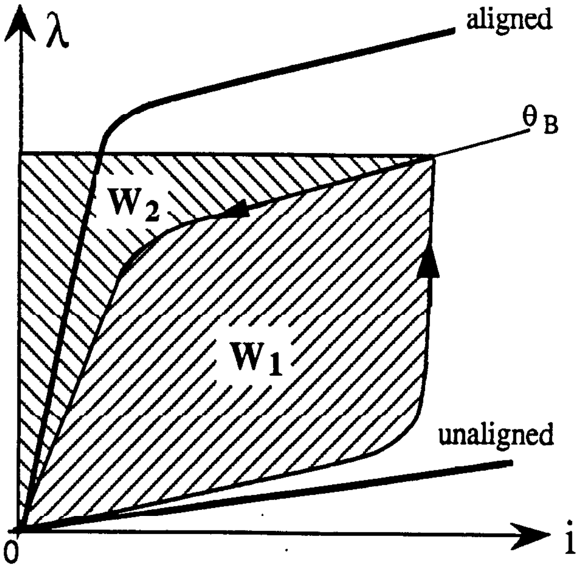


Fig. 1 Energy Conversion in One Stroke of a VRM

Thus far, numerous converters have been proposed to accomplish necessary current commutation of VRMs [9,10]. However, none of these converters can avoid the inherent tradeoff between semiconductor device ratings and motor specific output. That is, the higher the motor specific output, the higher the device voltage/current rating.

The method commonly used to tackle the second problem of energy circulation is to increase the saturation level. However, a higher saturation level leads to higher r.m.s. current and therefore higher losses [11]. As a means to increase the energy conversion ratio, a so-called premagnetization concept has been applied for use with a VRM structure [12,13]. However, while the energy conversion ratio can be somewhat improved by means of premagnetization, these two problems have, by no means, been completely solved.

II. PROPOSED MOTOR CONFIGURATION

Even though there are two problems to be solved there is, in reality, only one cause, the problem of trapped energy. Obviously, the short pitch windings in a conventional VRM can not, by themselves, perform the function of utilizing the trapped energy. On the other hand, this motor structure has several advantages which would be useful to retain. To implement a means of storing the magnetic field energy, an auxiliary winding can be introduced into a conventional VRM to form, in effect, a commutation winding. Hence, this machine can be considered as a Auxiliary Commutated Variable Reluctance Machine (ACVRM). With this commutation winding in place, an alternative switching concept can be implemented in two steps. In the first step the current in the short pitch winding being turned off can be transferred to the commutation winding and, consequently, the energy stored in the magnetic field is transferred to the commutation winding. In the second step the trapped energy is utilized in the commutation winding. To perform this desired function, the commutation winding should satisfy the following conditions:

(1) It should have good coupling with the short pitch winding to be turned off in order to rapidly absorb the trapped energy;
(2) Its self inductance should be independent of the rotor position in order to avoid the possibility of negative torque;
(3) It should retain a mechanism for converting the trapped energy to mechanical energy and/or transfer this energy to the field of next conducting phase.

Careful study of the stator and rotor structures of VRMs leads to the finding that a full pitch winding in a 6/4 VRM (six stator poles and 4 rotor poles) whose stator pole arc is thirty degrees and rotor pole arc equal to or greater than thirty degrees, can satisfy the above conditions. Based on this concept, the motor configuration shown in Fig. 2 is proposed. The idealized winding inductances of this new motor are shown in Fig. 3.

From Fig. 2 it can be seen that the full pitch winding (i.e. phase D) has good coupling with phase B which is to be turned off. This satisfies the first condition. Also from Fig. 2 it can be seen that the reluctance of the flux path of phase D is constant because the total overlapped area between the stator and rotor poles is unchanged. This satisfies the second condition. As discussed later, the trapped energy can partially transferred to the field of next phase and partially converted to mechanical energy through the interaction between the currents in phase D and next phase to be turned on. This satisfies the third condition.

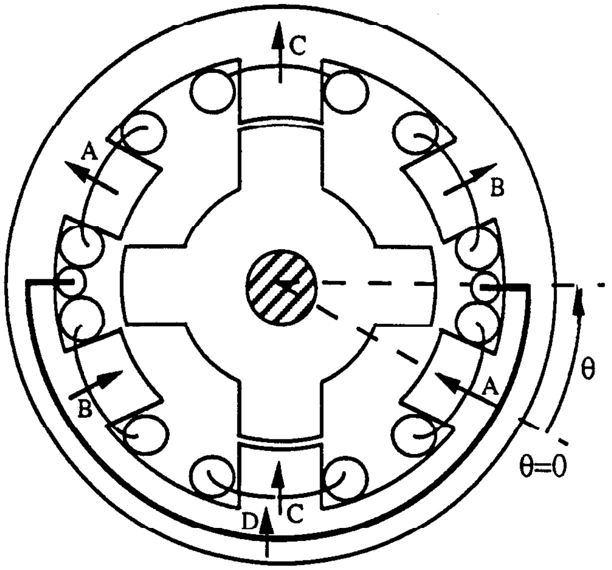


Fig. 2 Structure of Proposed Motor

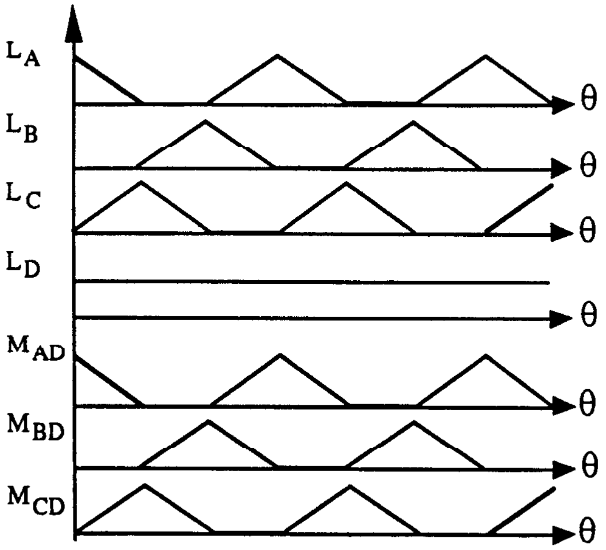


Fig. 3 Idealized Inductance Waveforms

III. OPERATING PRINCIPLES OF THE NEW MOTOR

3.1 Excitation of the Short Pitch Windings

The excitation of the short pitch windings is the same as that of conventional VRMs except the current in the winding can be turned off closer to the point of stator/rotor pole alignment for better utilization of the energy placed into the machine and therefore improved torque performance.

3.2 Turn-off of the Short Pitch Windings

In this section the turn-off process is analyzed first and then, based on the analysis three means to turn off a short pitch winding are proposed. To simplify the analysis two assumptions are made:

1. The inductance of a short pitch winding is constant during its turn-off period.

2. The effect of the current of the next phase in the turn-off process is negligible.

The first assumption is valid when the rotor pole arc is greater than thirty degrees. When the rotor pole arc is equal to thirty degrees, the first assumption is still a good approximation because the inductance change very little around the aligned position because of saturation. The second assumption is a good approximation because the coupling between phase D and next conducting phase is weak at this instant.

Assuming phase B is being turned off, the equations of the system are

$$V_B = R_B i_B + \frac{d\lambda_B}{dt} \qquad (1)$$

$$V_D = R_D i_D + \frac{d\lambda_D}{dt} \qquad (2)$$

$$\lambda_B = L_B i_B + M_{BD} i_D \qquad (3)$$

$$\lambda_D = L_D i_D + M_{BD} i_B \qquad (4)$$

$$L_B = K^* M_{BD} + L_{lB} \qquad (5)$$

$$L_D = M_{BD}/K + L_{lD} \qquad (6)$$

where K is the turns ratio $\frac{N_B}{N_D}$, M_{BD} is the mutual inductance, and L_{lB} and L_{lD} are leakage inductances.

From (1) to (6), neglecting the resistance of phase D, one obtains

$$V_B - K^* V_D = R_B i_B + \left(\frac{M_{BD}(L_{lD}K + L_{lB}/K) + L_{lD}L_{lB}}{M_{BD}/K + L_{lD}}\right)\frac{di_B}{dt} \qquad (7)$$

Neglecting the smaller terms $L_{lD}L_{lB}$ in numerator and L_{lD} in denominator, (7) can be simplified to the form,

$$V_B - K^* V_D = R_B i_B + (L_{lD}K^2 + L_{lB})\frac{di_B}{dt} \qquad (8)$$

It can be seen from (8) that the effective inductance faced by current i_B is on the order of the leakage inductance. This observation suggests that the current i_B can decay to zero in the ACVRM much more rapidly than it does in a conventional variable reluctance motor. In fact, the current (i.e. energy) in phase B is transferred to phase D because of the flux conservation principle. From (8) it can be seen that one can turn off phase B by

1) applying a negative voltages to phase B and short circuiting phase D; or

2) applying a positive voltage to phase D and short circuiting phase B; or

3) applying a negative voltages to phase B and a positive voltage to phase D.

In terms of performance, the third approach is the best because current i_B decays most rapidly in this case.

After current i_B reaches zero, phase B must be open circuited and phase D is short circuited. After the current in phase D decays to zero, phase D is then open circuited.

3.3 Utilization of the Trapped Energy

As pointed out above, the current in the short pitch winding is transferred to the full pitch winding during the turn-off process. As a result, the main flux remains in the motor and the energy associated with the main flux is transferred from phase B to phase D. It can be seen in Fig. 2 that as the rotor rotates, the overlapped area under the stator poles of next phase (e.g. phase A) is increasing while the overlapped area under the stator poles of phase B is decreasing. As a result, part of the flux, which links winding B and D originally, is shifted from the area under stator poles of phase B to the area under stator poles of phase A. Consequently, the field energy associated with this part of the flux is transferred to the field in the region under the stator poles of phase A. This means part of the field energy stored in phase D is directly transferred to the field of next phase.

It can been noticed from Fig. 3 that in the period when the self inductance of phase A is increasing the mutual inductance between phase D and phase A increases as well. As a result, a back EMF is induced in winding D after phase A is turned on. If phase A is energized in such a manner that the flux produced by its current is in the same direction as the flux produced by the current in phase D, then the induced back EMF (i.e. $i_A\frac{dM_{AD}}{dt}$) in phase D, as shown in Fig. 4, is positive. In this case the back EMF in phase D absorbs energy. As a result, part of the field energy stored in phase D is converted directly to mechanical energy. If the motor is not saturated the corresponding torque is given by

$$T = i_D i_A \frac{dM_{AD}}{d\theta} \qquad (9)$$

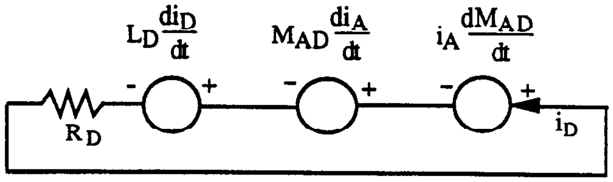


Fig.4 Equivalent Circuit of Phase D with Phase A on

As the energy stored in phase D transfers partially to the field of next phase, partially to the output and partially to the losses, the current in phase D decreases and finally decays to zero.

Figure 5 illustrates the energy conversion process in both a conventional VRM and the new auxiliary commutated VRM. The area W_1+W_5 represents the energy converted to mechanical form during one stroke of the conventional VRM. The area $W_1+W_2+W_3$ represents the energy converted in the new motor. The energy W_2 represents the increase in output due to the fact the current in the short pitch winding can be turned off closer to the point at which stator/rotor pole alignment is reached. The energy W_3 represents the energy converted from the field energy trapped within the motor to mechanical form. The energy W_4 represents the energy stored in the leakage field, which is returned to the source. Energy W_5 represents the field energy transferred from the field energy of the previously conducting phase. It is clear from Figure 5 that the ACVRM can have significantly higher output torque than a conventional VRM.

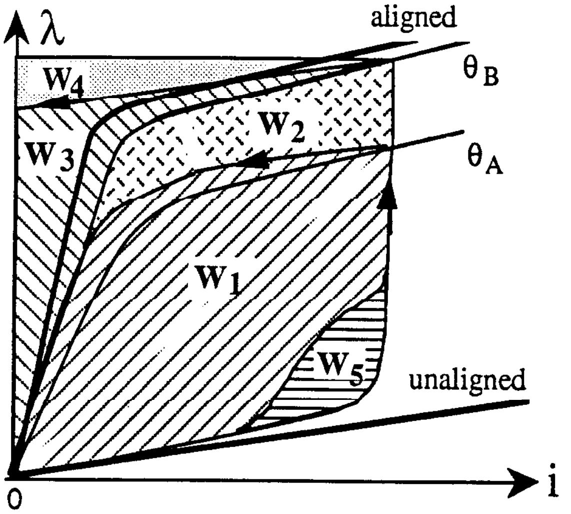


Fig. 5 Energy Conversion in the New VRM

Figure 6 shows the energy flow in the new auxiliary commutated VRM. It can be seen that only a small amount of energy, which is stored in the leakage field, need be returned to the source. This means the energy circulation problem is virtually solved in the new motor drive.

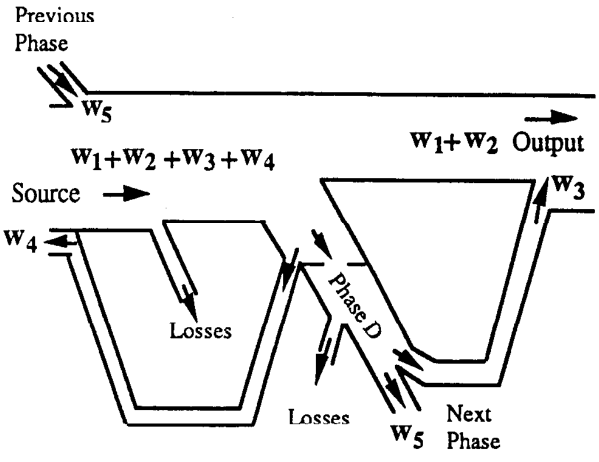
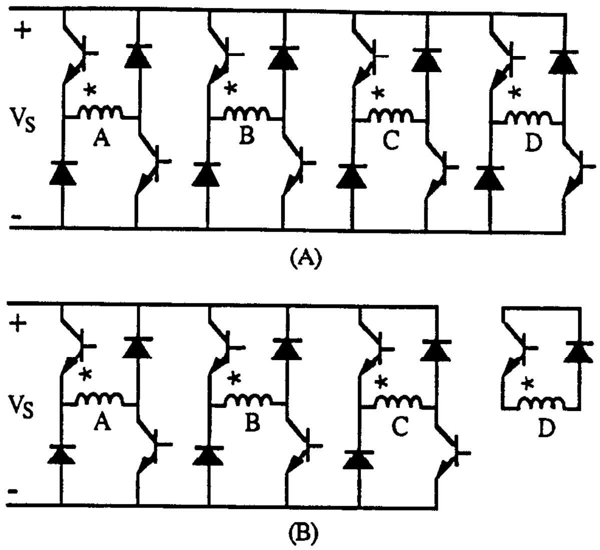


Fig. 6 Energy Flow in the New VRM System

IV. CONVERTER CONFIGURATIONS

Since the mechanism for turning off the short pitch windings in the new motor is different from that of conventional VRMs, this new motor configuration opens the door to numerous new converter topologies. Figure 7 shows two basic converters for the new motor. Converter A, shown in Fig. 7, can be used to implement any of the three switching strategies previously mentioned because any one of the four phases can be connected to either positive voltage, or negative voltage or be short circuited (zero voltage). To have the best performance, the short pitch winding to be turned off must be connected to a negative voltage through two freewheeling diodes and the full pitch winding must be connected to a positive voltage through two switches during the turn-off process. This converter functions better in terms of performance but has a drawback that it requires more devices. Converter B is simpler and cheaper, but it can not give the system as good performance as converter A since a positive voltage can not be applied to the full pitch winding to speed up the turn-off process. To provide more options for different tradeoff between the performance and the cost, the authors have proposed several other converter circuits [6]. A comparison of the performance and cost of these new converters will be presented in a future paper.



(A)

(B)

Fig. 7 Basic Converters for the New Motor

V. SIMULATION RESULTS

Even though VRMs have a simple structure and their operating principle appears to be straightforward, it is generally not easy to obtain an accurate performance prediction of its behavior because such machines are usually highly saturated. Since a mutual coupling is introduced between the full pitch winding and the other short pitch windings, it can be expected that the modeling of the ACVRM will be challenging. While nonlinear modeling and accurate performance prediction for the new motor are presently being developed, some quantitative ideas about the performance of this motor can be obtained from the results of a simulation based on a simple linear model. In this simulation the following assumptions are made :

1. There is no saturation or fringing.
2. The speed is constant.
3. There is no mutual coupling between the short pitch windings.

A conventional and a auxiliary commutated VRM have been simulated for comparison purposes. Both of the motors are identical except the new motor has a full pitch winding which is wound with the same wire cross section as the short pitch windings. The main parameters chosen for the two motors are as follows:

DC bus voltage:	100 V
Peak Current:	8A
Rated Speed:	1200 RPM
Rated Output:	300 W
Turns Ratio:	1
Stator Pole Arc:	30 Degree
Rotor Pole Arc:	32 Degree
Resistance of short pitch winding:	0.54 Ω
Resistance of full pitch winding:	0.91 Ω
Maximum Inductance/Phase:	62 mH
Minimum Inductance/Phase:	7.0 mH

The equations of the system are as follows

$$V_A = R_A i_A + \frac{d\lambda_A}{dt} \tag{10}$$

$$V_B = R_B i_B + \frac{d\lambda_B}{dt} \tag{11}$$

$$V_C = R_C i_C + \frac{d\lambda_C}{dt} \tag{12}$$

$$V_D = R_D i_D + \frac{d\lambda_D}{dt} \tag{13}$$

$$\lambda_A = L_A i_A + M_{AD} i_D \tag{14}$$

$$\lambda_B = L_B i_B + M_{BD} i_D \tag{15}$$

$$\lambda_C = L_C i_C + M_{CD} i_D \tag{16}$$

$$\lambda_D = L_D i_D + M_{AD} i_A + M_{BD} i_B + M_{CD} i_C \tag{17}$$

$$T = \frac{1}{2}\left(i_A^2\frac{dL_A}{d\theta} + i_B^2\frac{dL_B}{d\theta} + i_C^2\frac{dL_C}{d\theta}\right) + i_D\left(i_A\frac{dM_{AD}}{d\theta} + i_B\frac{dM_{BD}}{d\theta} + i_C\frac{dM_{CD}}{d\theta}\right) \tag{18}$$

In the simulation, the currents are solved from (10) to (17) after the voltages are determined according to the switching pattern and the rotor position. Torque is calculated from (18) once the currents have been calculated. For the purpose of modeling the conventional motor, the current i_D and flux λ_D are set to zero.

The turn-on angle is chosen to ensure that a phase current can reach the peak desired current at the point when the phase inductance begins to increase. The turn-off angle is chosen to realize the highest possible torque. For the conventional motor, a phase is connected to a negative voltage during its turn-off period. For the new motor, converter A shown in Fig. 7 is used and the third switching strategy mentioned above is employed. That is, a negative voltage is applied to the off-going phase while a positive voltage is impressed on phase D.

Two operating modes are simulated. One mode concerns low speed operation (chopping operation) and the other concerns high speed operation (single pulse operation). Figures 8 and 9 show the simulation results for the two motors operated in the chopping mode, while Figs. 10 and 11 show the simulation results of the two motors operated in the high speed mode.

The following observations can be made concerning the simulation results illustrated:

1. The currents in the short pitch windings of the ACVRM clearly decay to zero much more rapidly than they do in the conventional motor. This means the new motor does not suffer from the current commutation problem to the same degree as the conventional VRM.

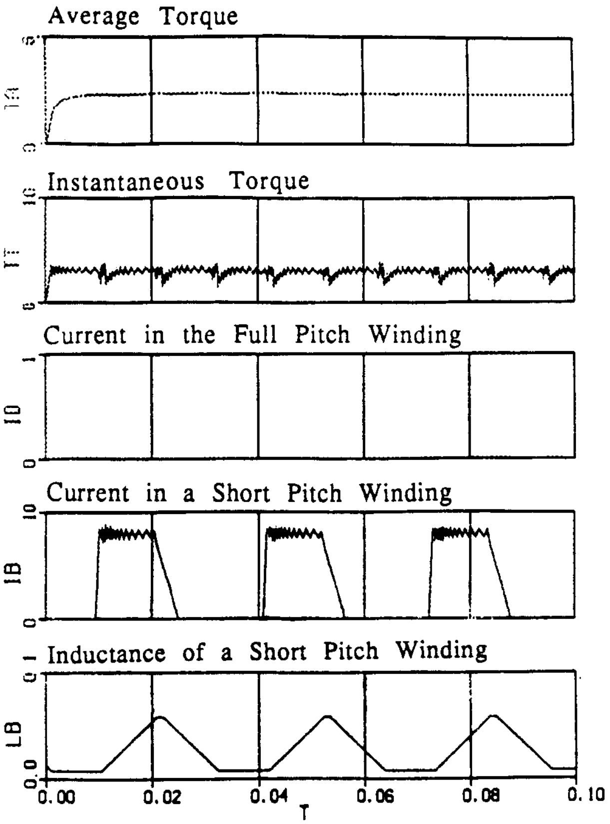


Fig. 8 Simulation Results of a Conventional VRM in Low Speed Operation (ω=0.4 p.u.)

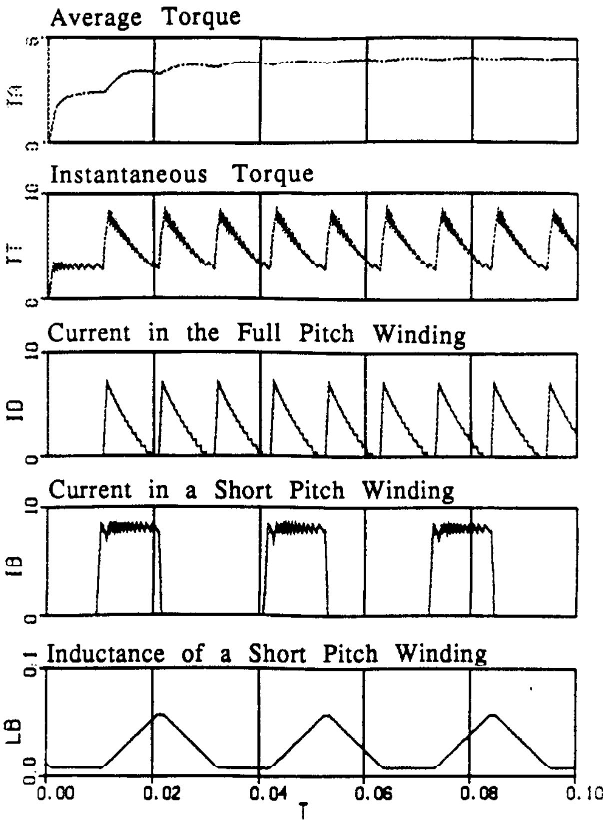


Fig. 9 Simulation Results of a New VRM in Low Speed Operation (ω=0.4 p.u.)

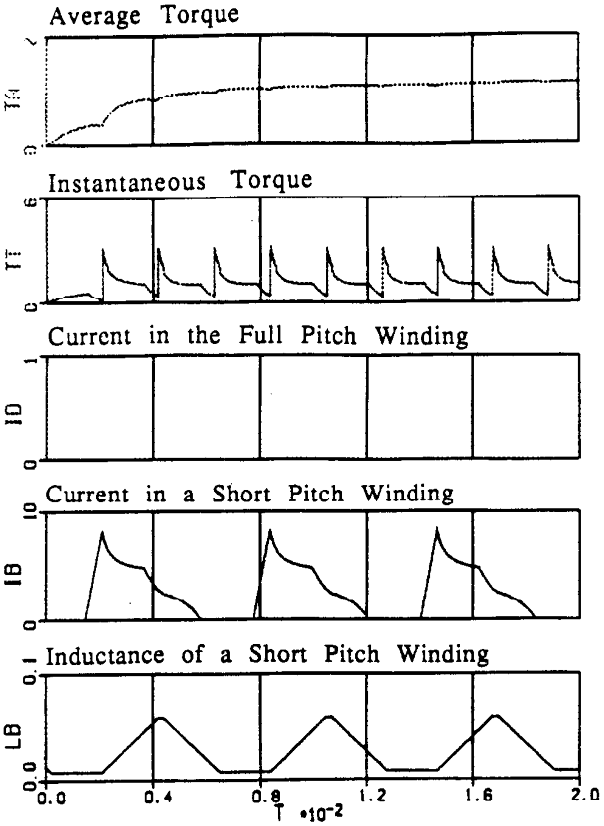


Fig. 10 Simulation Results of a Conventional VRM During High Speed Operation (ω=2.0 p.u.)

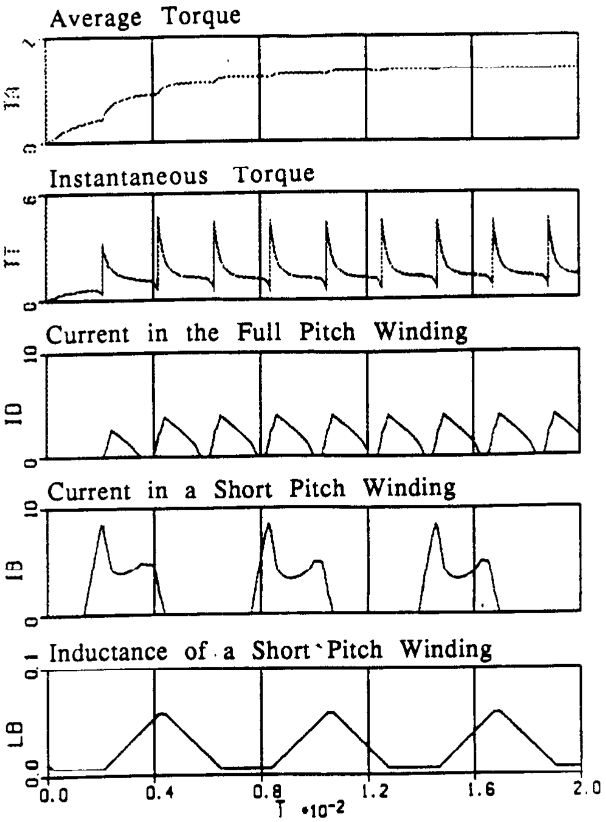


Fig. 11 Simulation Results of a New VRM During High Speed Operation (ω=2.0 p.u.)

2. The ACVRM has a higher output torque than the conventional motor for the same input current limit.

3. Both of the motors clearly have torque spikes which can be interpreted as a disadvantage. It should be pointed out, however, that the relatively higher torque spikes in the new machine are due to the fact that saturation and fringing are not taken into account in the simulation. It can be expected that the torque will be smoothed out to great extent in the actual motor.

4. The ACVRM has higher torque ripple, especially at low speed. The reason for this behavior is that in a linear model the torque component due to i_D, the current in the full pitch winding, is proportional to the product of i_D and the current in the short pitch winding which is conducting current, for example i_A. During low speed the back EMF is low and i_A can be regulated to nearly a constant value. Therefore the extra torque component decreases as the current i_D decreases while the torque component due to i_A is roughly a constant. At high speed the extra back EMF in the short pitch winding induced by i_D is high enough to cause a dip in the waveform of i_A. As a result, the torque component corresponding to current i_A has a dip which balances part of the torque component due to current i_D. Hence, the new motor has a smaller torque ripple at high speed than at low speed. It should be pointed out that the torque ripple of the new motor can be manipulated by controlling the currents in the short pitch windings as a function of the current in the full pitch winding and the torque ripple essentially eliminated. This subject is a topic for future research.

Figure 12 shows the speed-torque curves of the two motors calculated by means of simulation. To have a more meaningful comparison between the average torques of the two motors, the curve of the new motor is obtained under such constraint that the total copper loss of each motor is kept the same. It can be seen that at the same speed the new motor has significantly higher torque than the conventional motor even with the same copper loss. In another words during field weakening the ACVRM can operate at a substantially higher speed than the conventional VRM with the same torque.

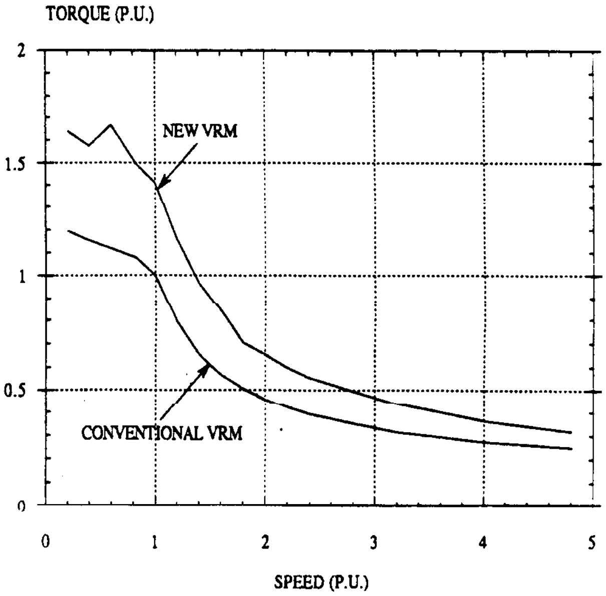


Fig. 12 Torque-Speed Curves

Even though the simulation results based on a linear model are not very accurate they do illustrate the performance improvements possible by the full pitch winding. Certainly the results of high speed operation are close to the reality because the motors are less saturated in high speed operation. At Wisconsin, a nonlinear model is presently being developed for more accurate performance prediction. A drive system employing the new motor is being built and the measured comparisons between the performance of the two motors will be reported in the near future.

VI. FUTURE RESEARCH

The authors believe that research on the type of motor drives described in the paper is just beginning. For example, an extension of the concept proposed in this paper is shown in Fig. 13. the authors have proposed another motor which have two full pitch windings and two short pitch windings. The operating principles are similar to those of the motor shown in Fig. 2. The advantage of the second motor over the ACVRM described in this paper is that the slot utilization is better. The authors are conducting research on the motor shown Fig. 13 and the results will also be presented in another paper.

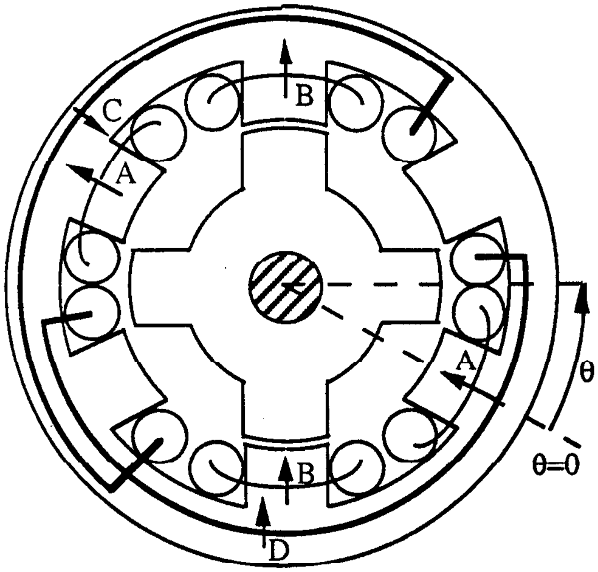


Fig. 13 Variable Reluctance Motor with Two Full Pitch Windings

In addition to the research mentioned above the authors are working in the following areas:

1. Additional converter topologies, including soft switching converters.
2. Torque ripple control.
3. Design optimization.
4. Elimination of position sensor.

VII. CONCLUSIONS

A new concept is proposed in this paper to solve the problems associated with the energy stored in the magnetic field in conventional VRMs. By retaining and utilizing the field energy within the machine by utilizing commutation windings, the new motors are free from current commutation problem and excitation penalty normally associated with variable reluctance motors. Consequently, compared with conventional VRMs the new motors have: (1) better turn-off and turn-on performance; (2) higher speed capacity; (3) higher torque density; and (4) potential for higher efficiency.

It should be mentioned in closing that Murphy's Law has yet to be repealed. The penalties paid for these advantages are: (1) more active copper is used; (2) more switching devices are required for the converter; (3) reliability is decreased since the three phase windings are no longer decoupled.

VIII. ACKNOWLEDGMENT

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